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QUASIPARTICLE HETERODYNE MIXING IN SIS TUNNEL JUNCTIONS,(U)

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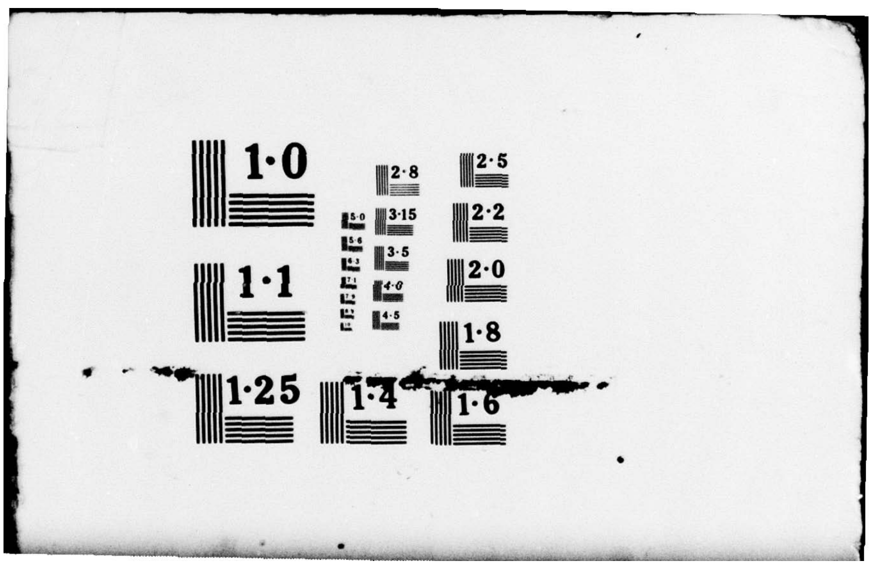
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(6) Quasiparticle Heterodyne Mixing in SIS Tunnel Junctions,[†]

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Abstract

The rapid onset of quasiparticle tunneling current in superconductor-insulator-superconductor (Josephson) junctions at voltages above $2\Delta/e$ is being used for millimeter wave heterodyne mixing. Junctions with $2\mu m$ diameter and $R_N = 50\Omega$ have little capacitive shunting at the signal frequency of 36 GHz. Because there is no series resistance, residual capacitance can be tuned out. Single sideband conversion efficiencies of 0.18 and mixer noise temperatures as low as $T_M \simeq 14K$ have been observed. Both results agree with shot noise limited mixer theory. Photon assisted tunneling effects are seen which indicate the approach to photon noise limited operation.

plus

delta

micron

approximately

INTRODUCTION

The ideal nonlinear element for a classical heterodyne mixer is a switch which can be driven between high and low resistance states by the local oscillator (LO). At microwave frequencies Schottky diodes with I-V characteristics of the form $I = I_o[\exp(SV)-1]$ are often used for this purpose. Conventional Schottky diodes have $S = e/kT = 40V^{-1}$ at 300 K and somewhat higher values at reduced temperatures. The nonlinearity in such diodes arises from thermally activated conduction and disappears at temperatures low enough that tunneling currents dominate. The super-Schottky diode[1] which operates by quasiparticle tunneling between a superconductor and a semiconductor has $S = 11{,}600^{-1}$ at T = 1K. Such a sharp corner on the I-V curve is of advantage for small signal receivers at short millimeter and submillimeter wavelengths because of the difficulty of obtaining large amounts of LO power at high frequencies and because LO noise problems are reduced. Low temperature operation also gives low mixer noise. The maximum operating frequency of these Schottky devices is set by the requirement that the junction capacitance discharge through the series (spreading) resistance of the semiconductor twice each cycle.

In principle a superconductor-insulator-superconductor (SIS) tunnel junction approaches the ideal switch limit more closely than the super-Schottky or related devices because the singularities in the density of states on both sides of the junction cause an extremely sharp onset of quasiparticle current at the full gap voltage $2\Delta/e$. In practice the S-values thus far obtained from Pb-In-Au alloy junctions in the 1.5 - 4.2 K temperature range are

comparable to an ideal Schottky at ~1.3K. An important feature of this device is the absence of series (spreading) resistance. External microwave circuit elements can thus be used to resonate out the junction capacitance. Since there are always practical limitations to the amount of capacitance which can be resonated, it is useful to inquire to what extent capacitance can be made unimportant by adjusting junction parameters. As the junction cxide thickness is reduced, R_N decreases exponentially, while C increases linearly. Consequently the importance of junction capacitance remains nearly constant if the normal state conductance per unit area, or equivalently the critical Josephson current density J_c, is scaled in proportion to frequency. We have $\omega CR_N \simeq 1$ at 36 GHz for junctions with critical current density $J_c = 10^3 A/cm^2$. In order to maintain suitable impedances for input and output coupling, the junction area must be scaled inversely with frequency. The need for very small junctions at high frequencies could be avoided by using several junctions in series. This would also increase the saturation level of the device. Since SIS junctions are being actively developed for other applications, a wide variety of junction parameters have been obtained. Junctions have been reported with high enough current density[2,3] to give good performance up to 900 GHz, beyond which mixing action will be degraded by the breaking of superconducting pairs.

JUNCTION FABRICATION

The Pb-In-Au alloy junctions used in these experiments were fabricated at NBS Boulder using the photoresist lift-off and RF sputter oxidation techniques.[4] The junction geometry is shown in Fig 1. The first electrode was evaporated

to a thickness of 4,100 Å on a Si substrate and subsequently covered with a 4,500 Å thick square of SiO. The SiO was then removed in the area of the desired junction and the junction oxide was grown by differential sputtering and oxidation. Finally a 5,000 Å thick counter electrode was added. A 0.28 ×1.0×19mm strip containing a single junction and its leads was separated by cleaving from the 40 junctions produced on each 5cm dia. Si wafer. The junction areas were varied from ~2 × 2 to ~4 × 4μm to provide a range of impedances.

MICROWAVE SYSTEM

The junction assembly was placed across a full height KA-band microwave waveguide in the E-field direction as shown in Fig. 1. The outer dimensions of the channel in which the substrate was placed were varied periodically to provide an RF choke. An adjustable stub $3\lambda/4$ in front of the junction and a plunger behind it completed the low temperature microwave circuit. Signal and LO power from carefully calibrated 36 GHz Klystrons were combined in a 10dB directional coupler and introduced into the cryostat through a section of stainless steel waveguide. Three identical 50Ω stainless steel IF cables were installed in the cryostat. One was terminated with a short circuit to measure IF cable losses, one was terminated in a 50Ω cold load to provide a noise source for calibrating the IF amplifier train, and one was connected to the mixer. A directional coupler was used to inject a signal into the mixer output to evaluate its coupling to the IF system. Measurements in the IF frequency band of 30-80 MHz were made using a string of transistor amplifiers with T_{IF} = 50K followed by a spectrum analyzer.

PERFORMANCE

The I-V curve of an SIS junction at 1.5K is shown at the top of Fig. 2 with P_{LO} = 0 and also with P_{LO} adjusted for optimum conversion efficiency.

The knee of the I-V curve corresponds to $S = 9{,}800\ V^{-1}$, compared with 7,730 for an ideal super-Schottky at the same temperature. The conversion efficiency and the noise in an SIS mixer are plotted on the same voltage scale at the bottom of Fig. 2. For $0 < V < 1.3mV$, the response is dominated by hysteretic Josephson mixing which is very noisy.[5] In junctions with larger values of zero voltage current, this response (and noise) was as much as one order of magnitude larger than shown, but could be supressed with a magnetic field. Above 1.3mV mixing occurs because of the two regions of curvature on the quasiparticle I-V curve. The noise in this voltage range is small and is independent of magnetic field. A periodic modulation of the quasiparticle mixing appears due to photon assisted tunneling because the range of voltage occupied by the knee of the static I-V curve is comparable to $h\nu/e$. This is the quantum correction to mixing calculated by Tucker.[6] The properties of two SIS mixers are shown in Table I.[7] The mixer performance has been calculated from the static I-V curve in each case using classical mixer theory and assuming that the capacitance has been resonated out at the signal frequency, but that the capacitance short circuits all harmonics.[8] This is a reasonable representation of our experiments because $\omega CR_N \gtrsim 1$. It may prove possible to obtain larger conversion efficiency in junctions with negligible capacitance by a more favorable termination of the harmonics. The calculated values of conversion efficiency and of mixer noise temperature assuming only shot noise are in reasonably good agreement with the measurements.

The present performance of the SIS mixer is sufficiently good to make practical applications very attractive. The stability and resistance to thermal cycling of the Pb-In-Au alloy junctions is a substantial advantage over the point contact Josephson mixer which had higher noise (T_M = 54K) and higher conversion efficiency = 1.3 at the same frequency.[9] The apparent ease with which operation can be extended to higher frequencies appears to be an advantage over the GaAs super-Schottky diode. The full benefit of this mixer will not be obtained unless an IF amplifier with T_{IF} ~1K can be developed.

TABLE I. Properties of two SIS mixers operated at 1.5K

J_c (A/cm^2)	R_N (Ω)	ωCR_N	T_M expt (K)	T_M theory (K)	L_c^{-1} expt	L_c^{-1} theory	P_{LO} (W)
390	100	2	14 ± 4	11	0.18	0.16	3×10^{-9}
710	52	1.4	21 ± 6	30	0.17	0.18	5×10^{-9}

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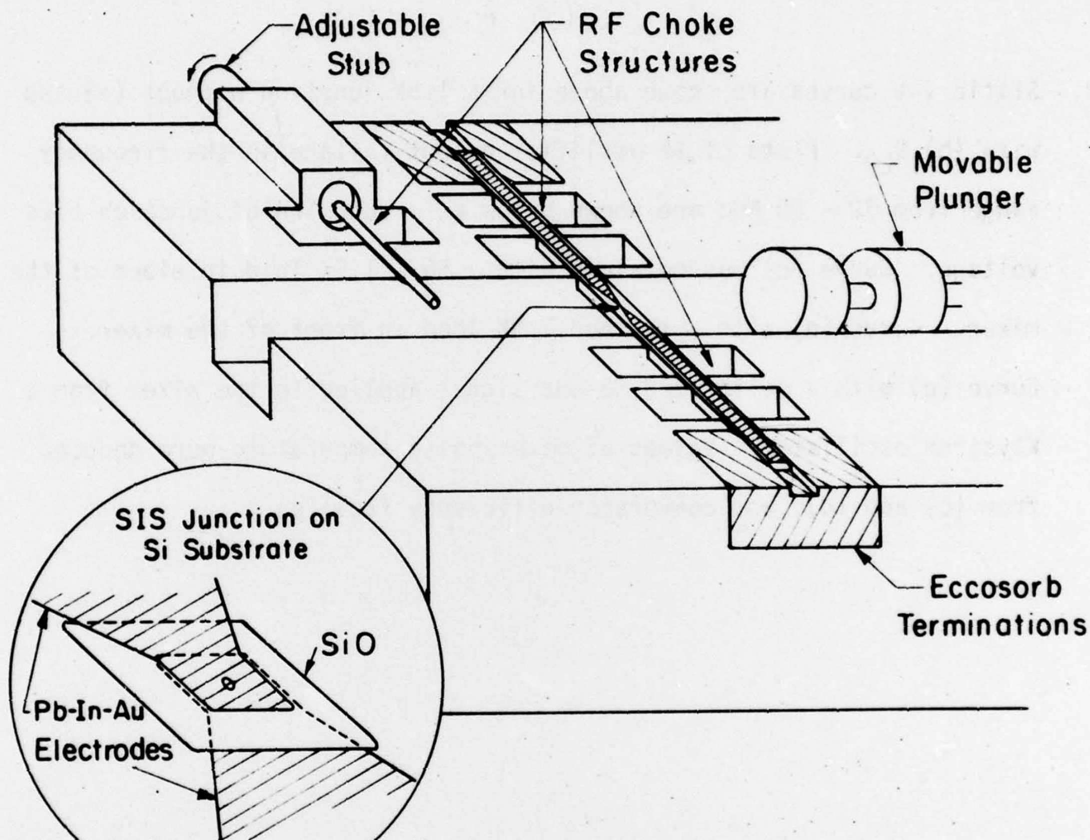
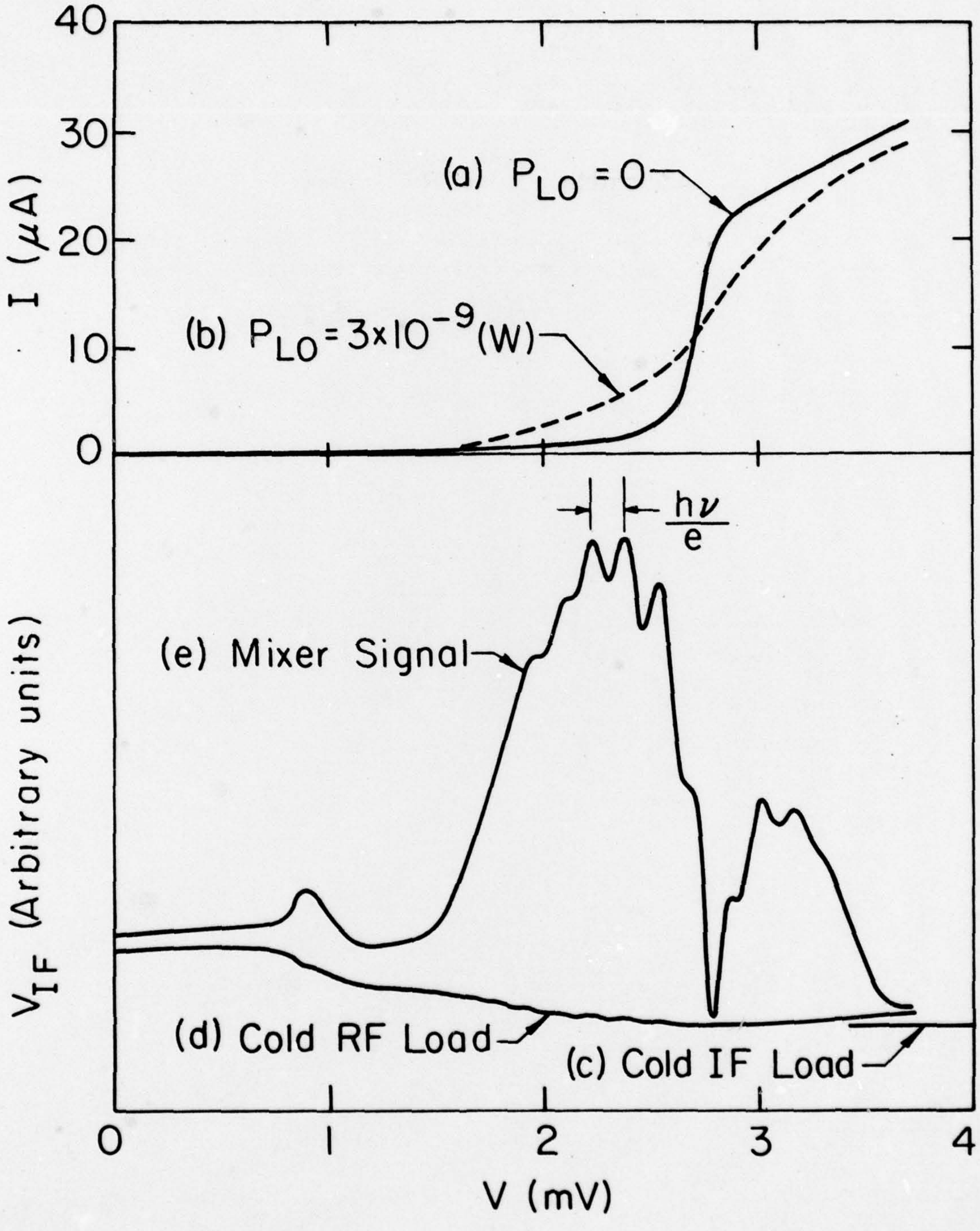
FIGURE CAPTIONS

1. Diagram showing the junction configuration and the arrangement of the junction in the 36 GHz mixer block.

2. Static I-V curves are shown above for a 1.5K junction without (a) and with (b) P_{LO}. Plots of IF amplifier output voltage in the frequency range from 30 - 80 MHz are shown below as a function of junction bias voltage. Curve (c) was obtained with a 50Ω, 1.5K load in place of the mixer. Curve (d) with a matched 1.5K load in front of the mixer. Curve (e) with a calibrated 36 GHz signal applied to the mixer from a Klystron oscillator. Values of mixer noise temperature were deduced from (c) and (d), and conversion efficiency from (e).



Adjustable
Stub
RF Choke
Structures
Movable
Plunger
SIS Junction on
Si Substrate
SiO
Pb-In-Au
Electrodes
Eccosorb
Terminations



40
30
20
10
0
I (μA)
(a) $P_{LO}=0$
(b) $P_{LO}=3\times10^{-9}$(W)
$\frac{h\nu}{e}$
(e) Mixer Signal
V_{IF} (Arbitrary units)
(d) Cold RF Load
(c) Cold IF Load
0
1
2
3
4
V (mV)